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Intercomparison of clumping index estimates from POLDER, MODIS, and MISR satellite data over reference sites

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Abstract

Clumping index is the measure of foliage grouping relative to a random distribution of leaves in space. It is a key structural parameter of plant canopies that influences canopy radiation regimes and controls canopy photosynthesis and other land-atmosphere interactions. The Normalized Difference between Hotspot and Darkspot (NDHD) index has been previously used to retrieve global clumping index maps from POLarization and Directionality of the Earth's Reflectances (POLDER) data at ~6 km resolution and the Bidirectional Reflectance Distribution Function (BRDF) product from Moderate Resolution Imaging Spectroradiometer (MODIS) at 500 m resolution. Most recently the algorithm was also applied with Multi-angle Imaging SpectroRadiometer (MISR) data at 275 m resolution over selected areas. In this study for the first time we characterized

40 and compared the three products over a set of sites representing diverse biomes and
41 different canopy structures. The products were also directly validated with both in-situ
42 vertical profiles and available seasonal trajectories of clumping index over several sites.
43 We demonstrated that the vertical distribution of foliage and especially the effect of
44 understory need to be taken into account while validating foliage clumping products
45 from remote sensing products with values measured in the field. Satellite
46 measurements responded to the structural effects near the top of canopies, while
47 ground measurements may be biased by the lower vegetation layers. Additionally,
48 caution should be taken regarding the misclassification in land cover maps as their
49 errors can propagate into the foliage clumping maps. Our results indicate that MODIS
50 data and MISR data, with 275 m in particular, can provide good quality clumping index
51 estimates at spatial scales pertinent for modeling local carbon and energy fluxes.

52

53 Keywords: Multi-angle remote sensing; MISR; MODIS; POLDER; vegetation clumping
54 index; hotspot; NDHD

55

56 **1. Introduction**

57 Leaves in canopies are generally grouped into various sub-canopy structures such
58 as tree crowns, branches and shoots. These structures make the leaf spatial distribution
59 non-random. The foliage clumping index (CI) is used to quantify the degree of deviation
60 of this distribution from the random case (Chen and Black, 1992; Nilson, 1971). A CI
61 value > 1 implies that the foliage is regularly distributed; a CI = 1 a random distribution
62 and if CI < 1 the foliage is more clumped than random (Chen et al., 2005; or see e.g.
63 Chen, 1996 for in-depth discussion). The CI is an important parameter for the correct
64 assessment of true leaf area index (L_t) from usually measured effective leaf area index
65 (L_e ; $L_t = L_e/CI$; Chen, 1996), and is also required for estimation of sunlit and shaded
66 leaf fractions in the canopy (Govind et al., 2013) and for accurate modeling of the
67 canopy-level gross primary production (GPP) (Baldocchi and Harley, 1995; Ryu et al.,

68 2011). Chen et al. (2012) recently showed that global GPP can be overestimated by as
69 much as 12% even when accurate L_t is available but clumping is ignored.

70 The CI can vary considerably even within a particular land cover type (Pisek et al.,
71 2011a), and it is highly desirable to map the spatial distribution of this index using
72 remote sensing data (Chen et al., 2003). Previous studies (Chen et al., 1999; Lacaze et
73 al., 2002) have shown that directional reflectance has a potential to estimate CI. Sensors
74 such as POLarization and Directionality of the Earth's Reflectances (POLDER; Deschamps
75 et al., 1994; Lier and Bach, 2008) and Multi-angle Imaging SpectroRadiometer (MISR;
76 Diner et al., 2002) are especially well suited for this purpose because they can acquire
77 surface reflectances at multiple view angles of the same ground position on one orbit.
78 POLDER is best used at the global scale because of its ~6 km nadir resolution and high
79 angular resolution while MISR can be used at both global and regional scales with its
80 275 m resolution. In turn, Moderate Resolution Imaging Spectroradiometer (MODIS) at
81 500 m resolution currently provides the finest pseudo multi-angular data for the global
82 land surface (Schaaf et al., 2002).

83 In this study we compared the most recent CI products from the respective
84 sensors (POLDER - Pisek et al., 2010a; MODIS - He et al., 2012; MISR - Pisek et al., 2013).
85 The evaluation of temporal and spatial consistency between the products was assessed
86 by using a) selection of sites representing the global distribution of biomes, b) a set of
87 sites with vertical profiles of clumping, and c) sites with available CI estimates covering a
88 complete seasonal cycle.

89

90 **2. Materials and Methods**

91 **2.1. Foliage clumping estimates from remote sensing data**

92 The main characteristics of the three most recent clumping products from the
93 different multi-angle sensors investigated in this work are listed in Table 1. The CI can be
94 estimated by using multi-angular remote sensing data because the variabilities in
95 reflectances for different sun-sensor configurations contain information about the
96 canopy structure (Goel, 1988; Li et al., 1995). The hotspot, where sun and view

97 geometry coincide, and the darkspot, where the reflectance is at its minimum, form the
98 basis of retrieving the clumping index from the angular signature in all three products.
99 The Normalized Difference Hotspot-Darkspot (NDHD) index either in the red or in the
100 near-infrared (NIR) band is linearly related to clumping index (Chen et al., 2003):

101

$$102 \quad CI=A(NDHD)+B \quad (1)$$

103

104 where A and B are coefficients determined by the linear regression, based on a set of
105 model simulations made with the 4-scale model in Chen et al. (2005). The coefficients
106 vary with solar zenith angle and assumed crown shape (see Table 2 in Chen et al., 2005).

107 The NDHD index is defined as:

108

$$109 \quad NDHD = (HS - DS)/(HS + DS) \quad (2)$$

110

111 where HS and DS are the reflectance at the hotspot and darkspot, respectively.
112 Clumping information is primarily in the darkspot reflectance, which contains a
113 maximum of visible shadows observed in the forward-scattering direction, where the
114 reflectance is minimum (Chen and Leblanc, 1997). Clumped canopies cast darker
115 shadows and decrease the darkspot reflectance (Leblanc et al., 2005a). The hotspot acts
116 as the normalizing factor that should minimize the dependence of the NDHD index on
117 foliage optical properties that are important determinants of bidirectional reflectance
118 (Asner et al., 1998).

119

120 **2.2. POLDER data**

121 The first global CI maps were derived using different generations of POLDER
122 sensors that measure directional and polarized reflectance with an approximately 6 km
123 nadir resolution (Chen et al., 2005; Pisek et al., 2010a). During a single satellite overpass,
124 a surface target was scanned up to 14 (POLDER 1) or 16 times (POLDER 3) under
125 different viewing angles, which also sampled the principle plane of the BRDF. It

126 therefore provided a direct measure of the hotspot and darkspot for NDHD calculation.
127 The final global CI map from POLDER observations (Pisek et al., 2010a) represents the
128 mean annual clumping values calculated from the successful retrievals of POLDER-1
129 (October 1996-June 1997) and POLDER-3 (the entire year 2005) (Fig. 1A). Gaps in the
130 global coverage by POLDER observations (5% of vegetated areas, mainly in the tropics
131 due to persistent cloud cover) were filled with mean CI values calculated from the
132 successful retrievals over the same biomes for the dominant land cover types from the
133 GLC2000 map. More details can be found in Pisek et al. (2010a).

134

135 **2.3. MODIS data**

136 He et al. (2012) derived a global CI map at 500 m resolution using the
137 bidirectional reflectance distribution function (BRDF) product in 2006 from MODIS
138 (Schaaf et al., 2002). While computing the NDHD using the red band (620-670 nm), He et
139 al. (2012) reported that the hotspot calculated from the MODIS BRDF product was
140 underestimated in comparison with POLDER measurements very near the hotspot.
141 Without correcting the bias in the MODIS data, the MODIS-derived CI could be
142 overestimated. He et al. (2012) developed an approach to correct the MODIS hotspot
143 magnitude with co-registered POLDER-3 data acquired at about the same time. After the
144 MODIS hotspot is corrected and the NDHD is calculated, the coefficients (A and B),
145 calculated from the second-order polynomial fit of the tabulated relationship between
146 CI and NDHD in Chen et al. (2005), were used to derive MODIS CI. He et al. (2012)
147 assigned a single annual CI value, the median from its noisy seasonal trajectory, to each
148 pixel in the map used in this study (Fig. 1B).

149

150 **2.4. MISR data**

151 MISR consists of nine cameras arranged to view along track that acquire image
152 data with nominal view zenith angles relative to the surface reference ellipsoid of 0.0° ,
153 $\pm 26.1^\circ$, $\pm 45.6^\circ$, $\pm 60.0^\circ$, and $\pm 70.5^\circ$ (forward and aftward of the Terra satellite) in four
154 spectral bands (446, 558, 672, and 866 nm). In the global mode, the 672 nm (red) band

155 images are acquired with a nominal maximum cross-track ground spatial resolution of
156 275 m in all nine cameras and information from all bands is provided at this resolution in
157 the nadir camera as well (Diner et al., 1998; 2002). Pisek et al. (2013) used the 275 m
158 resolution data to obtain surface bidirectional reflectance factors (BRFs). The Rahman–
159 Pinty–Verstraete (RPV) model (Rahman et al., 1993) was inverted against these full-
160 resolution BRF values in the red band. The initial hotspot (HS) and darkspot (DS) values
161 in the principal plane were reconstructed for solar zenith angle of 60° using the four
162 kernel coefficients for a given pixel from the RPV model inversion. Because the MISR-
163 hotspot might still be underestimated due to original data acquisition away from the
164 principal plane, the same hotspot correction of He et al. (2012) as in case of MODIS is
165 applied for MISR data as well. Using the above described approach, seasonal time series
166 of CI can be reconstructed from the available MISR observations for a given location.

167

168 **3. Methodology**

169 The intercomparison procedure was defined to comply as much as possible with
170 the best practices proposed by the CEOS WGCV LPV subgroup (Garrigues et al., 2008;
171 Baret et al., 2009). It corresponds to Stage 1 validation as defined by the CEOS
172 (Nightingale et al., 2011; Weiss et al., 2014). First we evaluated the consistency of the CI
173 products over selected locations (section 3.1.). Next, individual product accuracy was
174 assessed using a small set (< 30) of locations by comparison with reference in situ data
175 (section 3.2). We concluded with an assessment of how well the products compare with
176 the temporal changes in clumping over a subset sites with available in situ temporal
177 profiles of CI (Section 3.3).

178

179 **3.1. Pair-wise comparison over LPV/VALERI sites**

180 First we retrieved CI values from the corresponding products over a set of 63
181 globally distributed Land Product Validation (LPV) and VALidation of Land European
182 Remote sensing Instruments (VALERI) sites (Table 2) that represent a recommended
183 pool of sites for the systematic intercomparison of land biophysical products (Baret et

184 al., 2006; Garrigues et al., 2008; Nightingale et al., 2011). For analysis requiring direct
185 product-to-product comparison, the common approach is to resample them to 3 x 3
186 pixel size to reduce effects from co-registration inaccuracies and Point Spread Function
187 differences (see e.g. Camacho et al., 2013; D’Odorico et al., 2014). However, here
188 intercompared products contain clumping retrievals at very different spatial scales,
189 ranging from 275 m (MISR) to ~ 6 km (POLDER). Further resampling to 3 x 3 pixel size
190 would produce values at a scale (~18 km) with very little meaningful information.
191 Additionally, a single CI value was assigned to each pixel in global POLDER (Pisek et al.,
192 2010a) and MODIS maps (He et al., 2012), while MISR results have been presented so
193 far in the form of temporal trajectories over selected areas, where temporal resolution
194 varied based on the availability of good quality remote sensing data (Pisek et al., 2013).
195 The intercomparison retrievals were thus simply centered over each validation site.
196 MISR retrievals were made using the closest in time available good quality MISR BRF
197 data to the date of ground measurements of biophysical parameters at each site. Given
198 the fact that all three products used the identical NDHD-CI algorithm by Chen et al.
199 (2005) and MODIS and POLDER maps are already in the same (inverted sinusoidal)
200 projection, the differences between the individual products should highlight mainly the
201 changes in vegetation heterogeneity with spatial scale. The consistency is further
202 evaluated by intercomparing the bulk distribution of the available global product values
203 per biome type.

204

205 **3.2. Comparing clumping products with in situ measurements**

206 The CI products were validated over an additional global validation dataset with
207 measured vertical or temporal profiles of foliage clumping from Pisek et al. (2013) that
208 was further expanded with additional sites to represent all the main biomes. Detailed
209 site descriptions are provided in Table 3. The methodology to obtain in situ CI estimates
210 has been previously described in detail in Pisek et al. (2013). The field data should be
211 optimally integrated with high resolution imagery to allow a real product validation
212 (Morissette et al., 2006). Unfortunately, with only one exception of a limited extent high

213 resolution map of clumping index ($<1 \text{ km}^2$) by Simic et al. (2010), no such maps are
214 currently available, allowing only a limited evaluation. Due to the current absence of
215 high-resolution CI maps, the remote sensing retrievals were simply centered over each
216 validation site similarly to what was done in the previous section 3.1.

217

218 **3.2.1. Vertical profiles of clumping index**

219 In-situ measurements of CI at different heights using towers were available for
220 twelve of the field sites. We measured two northern boreal evergreen needleleaf stands
221 in Hyytiälä (61.85° N, 24.29° E) and Sodankylä (67.36° N, 26.64° E), Finland. Scots pine
222 (*Pinus sylvestris* L.) was dominant in both stands. The forest floor vegetation in Hyytiälä
223 was dominated by lingonberry, blueberry, lichens and mosses (Ilvesniemi et al., 2009)
224 and by fork moss with lichens at Sodankylä (Manninen et al., 2012). The third boreal
225 evergreen needleleaf stand was near Sudbury, Canada (47.16° N, 81.75° W). The
226 overstory vegetation was formed by short black spruce (*Picea mariana*) trees (~5.6 m);
227 the understory vegetation consisted mainly of feather moss (*Hylocomium splendens*)
228 with contributions from labrador tea (*Ledum groenlandicum*) and leather leaf
229 (*Chamaedaphne calyculata*) (Pisek et al., 2010b). All three boreal forest sites lacked a
230 tall understory vegetation.

231 The understory was also virtually missing at the three evergreen broadleaf forest
232 sites. The Mediterranean oak (*Quercus ilex*) stand in Castelporziano, Italy (41.71° S N,
233 12.38° E) contained only a few *Pistacia lentiscus* bushes in the understory layer. The
234 Wombat forest research site (-37.42° S, 144.09° E) is located in the Wombat State
235 Forest, Victoria, SE Australia. The site is a secondary re-growth *Eucalypti* forest that was
236 last harvested in 1980. Dominant tree species are Messmate Stringybark (*Eucalyptus*
237 *obliqua*), Narrow Leaf Peppermint (*Eucalyptus radiata*) and Candlebark (*Eucalyptus*
238 *rubida*) with an average canopy height of 25 m. The understory consists mainly of
239 patchy grasses. The second dry sclerophyll site at Whroo (-36.67° S, 145.03° E) in
240 Victoria, Australia is box ironbark woodland with lower tree height and canopy cover.
241 The vegetation was dominated by two main Eucalypt species: Grey Box (*Eucalyptus*

242 *microcarpa*) and Yellow Gum (*Eucalyptus leucoxylon*). The mean tree height at Whroo
243 was 15.3 ± 0.2 m.

244 Warra Long Term Ecological Research (LTER) site (-43.09° S, 146.66° E; Neyland et al.,
245 2000) is located in SW Tasmania, Australia. It represents a tall *Eucalyptus obliqua* wet
246 forest with rainforest understory and a dense man-fern (*Dicksonia antarctica*) ground-
247 layer. The forests around the Warra site had mature heights in excess of 55 m: the
248 tallest *E. obliqua* within the LTER reaches a height of 90 m.

249 Two native cloud rainforest stands were located in Thurston Lava Tube (19.41° N,
250 155.23° W) and Laupahoehoe (19.93° N, 155.29° W), Hawai'i, USA. The Thurston Lava
251 Tube site consists primarily of a single canopy species, ohi'a lehu (*Metrosideros*
252 *polymorpha*), with a dense understory layer of hapu'u ferns (*Cibotium* spp.) (Giambelluca
253 et al., 2009). Laupahoehoe had similarly comprised overstory with an additional
254 dominant species, Koa (*Acacia koa*) (Kellner and Asner, 2009).

255 The successional deciduous broadleaf stand in Morgan–Monroe State Forest
256 (39.32° N, 86.41° W) in Indiana, USA, was comprised predominantly of sugar maple
257 (*Acer saccharum*), tulip poplar (*Liriodendron tulipifera*), sassafras (*Sassafras albidum*),
258 white oak (*Quercus alba*), and black oak (*Quercus nigra*). The canopy vertical structure
259 was fairly consistent around the tower with peaks in L_t occurring at the crown level at
260 approximately 20–30 m and at the undergrowth level at approximately 0–10 m
261 (Oliphant et al., 2004).

262 The deciduous broadleaf type was also represented by an experimental plot
263 located in the state forest of Hesse (48.67° N, 7.06° E) in north east of France. The stand
264 was composed mainly (90%) of European beech (*Fagus sylvatica*) with a mean tree
265 height ~ 22 m. Due to canopy closure, understory vegetation is very sparse. Granier et
266 al. (2000) provide a more detailed description of the site.

267 A scaffolding tower in Järvelja, Estonia (58.27° N, 27.27° E) was located in a
268 hemiboreal-mixed stand with co-dominant species of silver birch (*Betula pendula* Roth.),
269 black alder (*Alnus glutinosa* L.) and Norway spruce (*Picea abies* (L.) Karst.). A suppressed

270 tree layer (mean height of 6.4 ± 0.6 m) was present around the tower and surrounding
271 forest (Noe et al., 2011).

272

273 **3.2.2. Seasonal variation of clumping index**

274 Seasonal trajectories of CI were available for four additional sites. Yatir forest,
275 Israel (31.35° N, 35.03° E), is a monoculture plantation which is dominated by Aleppo
276 pine (*Pinus halepensis* Mill.). Sparse understory vegetation develops only during the
277 rainy season (Nov–Mar) and disappears shortly thereafter (Grünzweig et al., 2003).
278 An oak-savanna ecosystem in California, USA (Tonzi; 38.43° N, 120.96° W), was
279 dominated by blue oak trees (*Quercus douglasii*) with occasional (<10%) gray pines
280 (*Pinus sabiniana*) (Baldocchi et al., 2004).

281 The third site with a seasonal trajectory of CI was a Scots pine (*Pinus sylvestris* L.)
282 stand in Järvelja, Estonia (58.31° N, 27.30° E). The site was very homogeneous with
283 respect to its horizontal structure and gap fraction (Pisek et al., 2011b). Forest
284 understory vegetation was composed of sparse labrador tea and cotton grass, and a
285 continuous *Sphagnum* moss layer. The site is included in the RAdiation transfer Model
286 Intercomparison (RAMI, <http://ramibenchmark.jrc.ec.europa.eu/HTML/Home.php>)
287 exercise (Kuusk et al., 2013).

288 The last validation site representing croplands was located at the Honghe Farm
289 (47.65° N, 133.52° E) in the Heilongjiang province, NE China. The area was dominated
290 with large homogeneous paddy rice fields (>5 km² homogeneity). The rice-cropping
291 practices were uniform, growing a single rice variety (*Japonica*) once a year during the
292 summer season (May to September).

293

294 **4. Results and Discussion**

295 **4.1. Pair-wise Product intercomparison over the LPV/VALERI sites**

296 The pair-wise comparisons between CI values from different products centered
297 over the 63 sites from LPV/VALERI networks are shown in Fig. 2. CI values from MODIS
298 and MISR showed the best overall agreement (Fig. 2A). This is not surprising, since the

299 two products use the same wavelength domain (visible red) for the CI retrieval and they
300 are also the closest in resolution scale (500 m vs. 275 m). The relative distribution of CI
301 values between vegetation types coincided between the two products as well.
302 Needleleaf forests are the most clumped vegetation type, followed by mixed and
303 deciduous forests, shrubs and crops, and with grasslands appearing to be the least
304 clumped (closest to the random distribution). The MODIS CI product indicated a much
305 wider CI range over intercomparison sites with needleleaf forests (0.47-0.72) compared
306 to MISR (0.52-0.59). Depending on the land cover, different coefficients were applied to
307 estimate CI from Eq. (1) (Chen et al., 2005). All MISR retrievals coincided with the
308 LPV/VALERI needleleaf designations over the respective sites. The MODIS CI product
309 uses the GLC2000 land cover map (Bartholome and Belward, 2005), which can differ
310 from the actual vegetation types present at individual LPV/VALERI sites. He et al. (2012)
311 previously noted that CI can be seriously biased by using a wrong land cover type. On
312 the contrary, in our study the MISR retrievals varied markedly over grasslands (0.52-1.0),
313 while MODIS retrievals were confined to much narrower range (0.72-0.86). There is no
314 specific algorithm for CI retrieval over non-forested areas; coefficients for broadleaf
315 trees are applied in the respective products over these areas, instead. The modeled
316 results by Chen et al. (2005) suggested that areas with less than 25% vegetation
317 coverage or fragmented land cover should be treated with caution. Our results confirm
318 this as well, especially retrievals over non-forested areas should be taken with pre-
319 caution. Interestingly, MODIS and MISR retrievals agree quite well over fields with crops
320 (Fig. 2A), which confirmed similarly homogeneous vegetation coverage at both scales of
321 275 m and 500 m over the majority of the intercomparison sites.

322 The distribution of CI values for needleleaf forests was more similar along the 1:1
323 line in case of the MODIS-POLDER pair-wise comparison (Fig. 2B). This is not surprising,
324 since both products use the same GLC2000 land cover map, and most of the
325 intercomparison sites with forests were located within larger areas with homogeneous
326 vegetation. Fig. 2B also confirmed that using different bands for the CI retrieval (red
327 from MODIS vs. NIR from POLDER) introduced no systematic bias. The POLDER CI

328 product included two clear outliers with very low CI values (high clumping) (Fig. 2B, C):
329 BOREAS BERMS (0.34) and Watson Lake (0.44). Given the location of the respective
330 sites, such values indicate the effects of topography on CI retrievals from POLDER data
331 had not been entirely removed by Pisek et al. (2010a). The MISR-POLDER comparison
332 offered the least agreement (Fig. 2C). The gradually decreasing agreement between
333 products from Fig. 2A to Fig. 2C confirmed the importance of using CI value
334 appropriately matched to the scale of the application in question (Ryu et al., 2010).

335 The mean CI and its one standard deviation for each GLC200 land cover types
336 from the available MODIS and POLDER global CI maps are shown in Table 4. There was
337 not much difference in CI value distributions from the two maps in Fig. 1 with exception
338 of needleleaf forests, where MODIS CI values appeared to be lower by ~ 0.1 than
339 POLDER retrievals. This agreed with the observations from Fig. 2B, suggesting that
340 despite the limited number of intercomparison sites Fig. 2 offered a good initial
341 overview of the differences between the CI products.

342

343 **4.2. Variation of clumping index across canopy depths**

344 It should be acknowledged that satellite measurements respond primarily to the
345 structural effects in upper levels of canopies. Chen et al. (2005) developed the CI
346 algorithms using L_t input and the resulting gap fraction simulated by the geometrical
347 optical model 4-Scale (Chen and Leblanc, 1997). The CI algorithm should enable the
348 correct retrieval of the stand average clumping of the leaves from remote sensing data.
349 On the other hand ground level CI measurements may be biased by presence of an
350 understory at forest sites, since the two layers can be differently spatially aggregated.

351 There was no pronounced tree/shrub understory layer at the first three
352 validation sites, representing boreal needleleaf forests (Fig.3A-C). In situ CI estimates
353 from different heights in the canopy were then very similar, which also confirms
354 previous modelling results by Nilson et al. (2011). The three needleleaf sites with vertical
355 profiles represent forests with different age, height, and species. There was a close
356 agreement of MISR CI retrievals with in situ CI values in all three cases. The MISR CI

357 values also agreed quite well with available in situ measurements over VALERI
358 intercomparison sites (Table 2). This suggests that MISR was indeed capable of
359 producing quality CI estimates over this vegetation type. MODIS CI values were also
360 comparable with in situ measurements over two needleleaf sites with exception of
361 Hyytiälä (Fig. 3A). However, Pisek and Oliphant (2013) previously noted that this
362 disagreement was due to wrongly assigned broadleaf forest GLC2000 land cover type
363 over this site. If the MODIS pixel with the Hyytiälä site was classified correctly as a
364 needleleaf forest, the retrieved MODIS CI value (0.53) agreed well with the CI measured
365 at the ground (0.52). The differences between assigned land cover types in the GLC2000
366 map and identified in immediate area around towers in Hyytiälä and Sodankylä (Table 1)
367 also explained the very different POLDER CI values. When the land cover is very
368 homogeneous and matching dominant vegetation type was assigned (Sudbury; Fig. 3C),
369 POLDER CI value was very close to the in situ CI measurements as well.

370 Similarly good agreement between ground level in-situ, MISR, and MODIS CI
371 retrievals was observed at eucalypt sites in Australia (Fig. 3D-F). The Whroo tower (Fig.
372 3E) was located rather close to the edge of the forest – the MISR CI value at 275 m still
373 picks up the signal from the surrounding forest area, while MODIS and POLDER signals at
374 coarser resolutions are already clearly influenced by the surrounding non-forested (less
375 clumped) area. In the POLDER case such influence was evident over the Wombat site as
376 well (Fig. 3D). Castelporziano represented another validation site without pronounced
377 understory vegetation. The state forest reserve around the tower was large enough to
378 occupy the full footprint of POLDER sensor, and POLDER CI value then offered the best
379 match with the in situ measurements (Fig. 3G).

380 There was a pronounced understory layer present at the remaining sites with
381 evergreen vegetation and measured vertical profiles of clumping (Fig. 3H-I). The
382 remotely sensed CI values can then differ from CI measured at the ground. In the native
383 cloud forests in Hawai'i (Fig. 3H-I), large gaps between tree crowns at upper levels of the
384 canopy may not be measured near the ground due to occlusion by lower vegetation fern
385 branches. Instead, the MISR CI values in particular were close to in situ measurements

386 obtained above the nearly uniform understory fern layer at ~6 m (Fig. 3H–I). The vertical
387 profile at Thruston Lava Tube site differed from Laupehoehoe because there was an
388 additional dominant species *A. koa* in the overstory at Thruston Lava Tube. There was a
389 frequent cloud cover over both Hawai'i sites which severely limits the opportunities for
390 acquiring good quality remote sensing data. Due to the missing data, the POLDER CI
391 value (0.64) over the two sites was originally filled and corresponded to mean CI value
392 calculated from the successful retrievals over the same biome (Pisek et al., 2010a). Such
393 values need to be treated with caution, as they obviously cannot correctly reflect
394 possible local variations in vegetation structure (Fig. 3H–I).

395 A suppressed tree layer was also present at the two broadleaf stands in Indiana
396 (Fig. 3J) and Estonia (Fig. 3K). The best agreement between satellite and field CI values
397 both at MMSF and in Järvelja was again achieved for observations taken above the
398 understory layer (Fig. 3J–K). Results over Hesse (Fig. 3L) documented that CI retrievals
399 from remote sensing data can match the ground in situ measurements in deciduous
400 broadleaf forests if the land cover vegetation type is correctly assigned, the forest area
401 is sufficiently large, and there is no pronounced shrub/tree understory layer.

402

403 **4.3. Seasonal variation of clumping index**

404 The land surface modeling community has assumed that clumping is constant
405 over seasons (Baldocchi et al., 2002; Houborg et al., 2009; Sampson et al., 2006) and
406 thus its temporal variation has been ignored. Fig. 4 shows the clumping may change
407 with season even for evergreen needleleaf forests due to needle phenology (Sprintsin et
408 al., 2011). At Yatir and Tonzi the POLDER CI values matched quite well the seasonal
409 clumping minima (Fig. 4A,B). Clumping was underestimated in both maps from POLDER
410 and MODIS over Järvelja RAMI stand (Fig. 4C). Similarly to the Hyytiälä case (Fig. 4A),
411 this disagreement was caused by wrongly assigned forest GLC2000 land cover type over
412 this site (He, pers. comm.). MODIS and POLDER CI values closely matched the in situ
413 measurements in Järvelja RAMI stand after assigning the correct land cover type
414 (needleleaf). The POLDER CI value did not agree with seasonal clumping minima from in

415 situ measurements at Honghe site (Fig. 4D). This was due to insufficient vegetation
416 coverage for correct clumping information retrieval from the satellite data at the
417 beginning and the end of season. MISR CI seasonal minima also leveled off around the
418 same value as POLDER (0.84; Fig. 4D), confirming the effect of insufficient vegetation
419 coverage during the non-growing season at non-evergreen sites. Fig. 4 illustrates the
420 potential of MISR to track successfully the seasonal trajectories of clumping. The
421 retrieved trajectories were also rather stable. No smoothing algorithm was applied
422 within the MISR CI processing chain (Pisek et al., 2013). The stability is not surprising
423 since the primary mission of the MISR instrument was to study the Earth atmosphere
424 and, in particular, to characterize atmospheric aerosols and clouds (Diner et al., 1998;
425 Verstraete et al., 2012). Significant efforts have been invested to address these issues in
426 great detail (Diner et al., 2005) and provide quality Level 2 products that are utilized to
427 convert MISR TOA BRF into surface BRF values at 275 m resolution. At the same time,
428 the MISR product quality requirements are rigorous (Bothwell et al., 2002), and no good
429 quality Level 2 data may be available for extended periods of time (Fig. 4C,D). Fig. 4C,D
430 demonstrates that gaps in seasonal trajectory of CI can be effectively filled using MISR
431 observations from other years over sites with stable land cover, when the atmospheric
432 conditions were more favorable.

433

434 **4. Conclusion**

435 In this study we compared the most recent CI products from the space-borne
436 multi-angular POLDER, MODIS, and MISR sensors for the first time. This exercise
437 corresponded to Stage 1 validation as defined by CEOS (Nightingale et al., 2011; Weiss
438 et al., 2014). Our main results highlight the following:

- 439 1) Satellite measurements responded to the structural effects near the top, while
440 ground measurements may be biased by the lower vegetation/understory layers.
- 441 2) POLDER CI map (Pisek et al., 2010a) may be used to predict the upper boundary
442 of seasonal clumping. The coarse spatial resolution of the POLDER map at ~ 6 km
443 presents the main challenge for the product validation with in situ measurements.

444 3) CI values in MODIS global clumping map by He et al. (2012) corresponded to the
445 median CI from the seasonal trajectories of clumping. The MODIS CI map by He et al.
446 (2012) with its spatial resolution at 500 m compared to ~ 6 km from POLDER might be
447 also more suitable given the spatial resolution of current land surface models (e.g.
448 Houborg et al., 2009).

449 4) If more detailed information is required, MISR retrievals can track correctly
450 seasonal developments of clumping as well.

451 5) Correct land cover information (deciduous vs. needleleaf) is crucial for retrieving
452 accurate CI value. Furthermore, space-borne sensors cannot provide correct CI
453 estimates over areas with insufficient vegetation coverage (<25%).

454

455 The field data should be optimally integrated with high resolution imagery to allow a
456 more thorough product validation and intercomparison (Morissette et al., 2006). The
457 current lack of such high resolution CI maps presents the main challenge for the next,
458 more in-depth validation stages as defined by CEOS. Given the previously documented
459 importance of foliage clumping on correct estimation of global terrestrial gross primary
460 productivity (e.g. Chen et al., 2012; Ryu et al., 2012), production of higher resolution
461 maps of foliage clumping, such as using UAVs equipped with BRF sensors (Kuusk et al.,
462 2014), is strongly encouraged.

463

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476

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Tables
Table 1. Characteristics of the Foliage Clumping Products under Study

Name	Spatial resolution	Algorithm	Parameterization	Global map	Temporal smoothing	References
POLDER	~ 6 km	model derived NDHD(NIR)-CI relationship	vegetation type	yes	No	Pisek et al. (2010a)
MODIS	500 m	model derived NDHD(red)-CI relationship	vegetation type	yes	Yes	He et al. (2012)
MISR	275 m	model derived NDHD(red)-CI relationship	vegetation type	possible	No	Pisek et al. (2013)

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Table 2. Overview of the LPV/VALERI Validation Sites

Network	Site	Country	Lat (deg)	Lon (deg)	Land cover
LPV	Aek Loba	Indonesia	2.63	99.58	palm tree plantation
LPV	Albemarle	NC, USA	36	-78	ENF
LPV	Alpilles2	France	43.81	4.71	crops
VALERI	Barrax	Spain	39.07	-2.1	crops
LPV	Bondville	IL, USA	40.01	-86.29	crops
LPV	BOREAS NSA	Canada	55.87	-98.48	ENF
LPV	BOREAS SSA BERMS	Canada	53.65	-105.32	ENF
LPV	Brasschaat (De Inslag)	Belgium	51.3	4.51	MF
VALERI	Cameron	Australia	-32.6	116.25	EBF
VALERI	Chilbolton	UK	51.16	-1.43	crops and forest
VALERI	Concepcion	Chile	-37.47	-73.47	MF
LPV	Counami	French Guyana	5.35	-53.24	EBF
VALERI	Counami	French Guyana	5.35	-53.24	EBF
VALERI	Demmin	Germany	53.89	13.21	crops
VALERI	Donga	Benin	9.77	1.78	grassland
LPV	Flakaliden	Sweden	64.11	19.45	ENF
LPV	Fundulea	Romania	44.41	26.58	crops
VALERI	Gilching	Germany	48.08	11.32	crops and forest
VALERI	Gnangara	Australia	-31.53	115.88	EBF
LPV	Gourma	Mali	15.32	-1.55	grassland
LPV	Guanacaste	Costa Rica	10.87	-85.66	tropical dry forest
VALERI	Haouz	Morocco	31.66	-7.6	crops
LPV	Harvard Forest	MA, USA	42.5393	-72.1779	DBF
VALERI	Hirsikangas	Finland	62.64	27.01	ENF
VALERI	Hombori	Mali	15.33	-1.48	grassland
VALERI	Hyytiälä	Finland	61.85	24.29	ENF
LPV	Järvselja	Estonia	58.31	27.3	ENF
LPV	Kejimikujik NP	Canada	44.45	-65.28	MF
LPV	Konza Prairie	KS, USA	39.09	-96.57	crops
LPV	Krasnoyarsk	Russia	57.27	91.6	ENF
LPV	Laprida	Argentina	-36.99	-60.55	grassland
VALERI	Laprida	Argentina	-36.99	-60.55	grassland
VALERI	Larose	Canada	45.38	-75.22	MF
VALERI	Le Larzac	France	43.9375	3.123056	grassland
LPV	Los Inocentes	Costa Rica	11.01	-85.49	tropical moist forest
LPV	Maun	Botswana	-19.92	23.59	herbaceous
LPV	Metolius (old pine)	OR, USA	44.49	-121.62	ENF
LPV	Metolius (young pine)	OR, USA	44.43	-121.56	ENF
LPV	Mongu	Zambia	-15.44	23.25	shrubs
LPV	Nezer	France	44.57	-1.04	ENF
LPV	Okwa River	Botswana	-22.41	21.71	shrubs
LPV	Park Falls	WI, USA	45.946	-90.272	ENF
VALERI	Plan De Dieu	France	44.2	4.95	crops
LPV	Puechabon	France	43.72	3.65	EBF
LPV	Romilly-sur-Seine	France	48.44	3.77	crops
VALERI	Rovaniemi	Finland	66.46	25.35	ENF
LPV	Ruokolahti	Finland	61.53	28.71	ENF
LPV	Sevilleta	NM, USA	34.35	-106.69	shrubs
LPV	Siera Chincua	Mexico	19.82	-100.28	ENF

VALERI	Siera Chincua	Mexico	19.82	-100.28	ENF
LPV	Skukuza	South Africa	-25.02	31.497	shrubland/woodland
VALERI	Sonian	Belgium	50.77	4.41	ENF
VALERI	Sud-Ouest	France	43.51	1.24	crops
LPV	Tapajos	Brazil	-2.857	-54.959	EBF
LPV	Ticino	Italy	45.201	9.058	poplar plantation
LPV	Tshane	Botswana	-24.16	21.89	herbaceous
LPV	Turco	Bolivia	-18.24	-68.18	shrubs
VALERI	Wankama	Niger	13.65	2.64	grassland
LPV	Watson Lake	YK, Canada	60.09	-129.38	MF
LPV	Whitecourt	AB, Canada	54.03	-115.78	MF
VALERI	Zhang Bei	China	41.28	114.69	grassland

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Table 3. Characteristics of the Validation Sites with Vertical or Seasonal Profiles of Clumping

Site	Location	Lat	Lon	Forest type	Overstory	Mean tree height (m)	Understory	Reference	in-situ data collection
Hyytiälä	Finland	61.85	24.29	NEF	SP	16	lingonberry, blueberry and mosses	Ilvesniemi et al. (2010)	2001/11
Sodankylä	Finland	67.36	26.64	NEF	SP	12	lichen, fork moss	Rautiainen et al. (2007)	2007/9
Sudbury	Canada	47.16	-81.75	NEF	BS	5.6	feather moss, labrador and leather tea	Pisek et al. (2010b)	2007/6
Laupahoehoe	HI, USA	19.93	-155.3	EBF	M,K	19	Cibotium spp.	Kellner & Asner (2009)	2013/1
Thurston Lava Tube	HI, USA	19.41	-155.2	EBF	M	14.5 ± 1.4	Cibotium glaucum (3.8 ± 2.7 m)	Giambelluca et al.(2009)	2010/9
Castelproziano	Italy	41.71	12.38	EBF	MEO	16	Pistacia lentiscus	Fares et al. (2014)	2014/6
Wombat	Australia	-37.42	144.09	EBF	EO, ERa, ERu	25	patchy grass	Haverd et al. (2013)	2013/7
Whroo	Australia	-36.67	145.03	EBF	EM, EL	15.3 ± 0.2	patchy grass	New site	2013/7
Warra	Australia	-43.09	146.66	EBF	EO	55	Nothofagus cunninghamii, Atherosperma moschatum, Eucryphia lucida, Phyllocladus aspleniifolius	Neyland et al. (2000)	2013/8
Järvelja	Estonia	58.27	27.27	MF	SB, BA,NS	17	Suppressed tree layer (mean height of 6.4 ± 0.6 m)	Noe et al. (2011)	2011/7
Morgan-Monroe State Forest	IN, USA	39.32	-86.41	BDF	SM, TP, S,WO,BO	27	Max. understory height 10 m	Oliphant et al. (2006)	2005/6
Hesse	France	48.67	7.06	BDF	EB	22		Longdoz et al. (2008)	2014/8
Yatir	Israel	31.35	35.03	NEF	AP	8	sparse grass (Nov-Apr)	Sprintsin et al. (2011)	2005
Tonzi	CA,USA	38.43	-121	S	BIO,GP	9.4±4.3	grass	Ryu et al. (2012)	2009/7-2010/3
RAMI pine	Estonia	58.31	27.3	NEF	SP	16	Ledum palustre, Eriophorum vaginatum, continuous Sphagnum ssp. moss layer	Kuusik et al. (2013)	2011/4-10
Honghe	China	47°39.11' N	133°31.31' E	CRO				Fang et al. (2014)	2012/6-10

In the column "Forest type" NEF – needleleaf evergreen forest, EBF – evergreen broadleaf forest, BDF – broadleaf deciduous forest, MF – mixed forest, S – savanna, CRO - cropland. In the column "Overstory" SP – Scots pine, M - *Metrosideros polymorpha*, K – *Koa*, MEO – Mediterranean oak, EO - *Eucalyptus obliqua*, Era - *Eucalyptus radiata* (narrow leaf peppermint), ERu - *Eucalyptus rubida* (candlebark), EM - *Eucalyptus microcarpa* (Grey Box), EL - *Eucalyptus leucoxyton* (Yellow Gum), SM – sugar maple, TP – tulip poplar, S - *Sassafras*, WO – white oak, BO – black oak, SB – silver birch, BA – black alder, NS – Norway spruce, EB – European beech, AP – Aleppo pine, BIO – blue oak, GP – gray pine.

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Table 4. CI product characteristics by biome (Average statistics calculated over vegetated areas)

GLCC2000 land cover type	Polder-3		MODIS	
	mean	standev	mean	standev
Tree cover, broadleaf, evergreen	0.64	0.11	0.66	0.05
Tree cover, broadleaf, deciduous, closed	0.69	0.08	0.7	0.04
Tree cover, broadleaf, deciduous, open	0.72	0.05	0.72	0.03
Tree cover, needleleaf, evergreen	0.63	0.12	0.53	0.04
Tree cover, needleleaf, deciduous	0.78	0.07	0.57	0.03
Tree cover, mixed leaf type	0.72	0.11	0.69	0.04
Tree cover, regularly flooded, fresh water	0.67	0.15	0.67	0.05
Tree cover, regularly flooded, saline water	0.78	0.17	0.71	0.06
Mosaic: Tree cover/other natural vegetation	0.7	0.05	0.71	0.04
Tree cover, burnt	0.78	0.15	0.7	0.04
Shrub cover, closed-open, evergreen	0.77	0.17	0.71	0.05
Shrub cover, closed-open, deciduous	0.74	0.09	0.74	0.04
Herbaceous cover, closed-open	0.77	0.12	0.75	0.05
Sparse herbaceous or sparse shrub cover	0.78	0.16	0.76	0.05
Reg. flooded shrub and/or herbaceous cover	0.8	0.14	0.73	0.04
Cultivated and managed areas	0.78	0.11	0.75	0.04
Mosaic: cropland/tree cover/natural veg	0.77	0.12	0.7	0.04
Mosaic: cropland/shrub and/or grass cover	0.76	0.05	0.75	0.04

839 **Figures**

840 Fig. 1. Global maps of foliage clumping from POLDER (A) and MODIS (B).

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842 Fig. 2. Intercomparison of the foliage clumping products over LPV/VALERI sites. BF-
843 broadleaf forests, NF-needleleaf forests, MF – mixed forests. The terms B and S represent
844 the mean and the standard deviation of the difference between the retrievals displayed
845 in the x axis and those shown in the y axis.

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847 Fig. 3. Vertical profiles of foliage clumping from in-situ measurements with ± 1 standard
848 deviation bars. Clumping index values from MISR data obtained around the same time
849 are marked with vertical dashed red line; MODIS - blue dotted line; POLDER - grey thick
850 dashed line. The mean height of undergrowth layer is marked by a green horizontal
851 dashed line; green areas mark the ± 1 standard deviation area. (For interpretation of the
852 references to color in this figure legend, the reader is referred to the web version of this
853 article.)

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855 Fig. 4. Seasonal profiles of foliage clumping for (A) Yatir, Israel, (B) Tonzi, CA, USA, (C)
856 Järvelja RAMI pine stand, Estonia, and (D) Honghe farm, China. Field measurements at
857 all four sites were taken above ground layer vegetation (if present).

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